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METEOROLOGICAL CONDITIONS DURING THE FORMATION OF ICE ON AIRCRAFT

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Weather Bureau

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INTRODUCTION

The hazard resulting from the formation of ice on airplanes makes it highly desirable to ascertain all possible meteorological information pertinent thereto in order to avoid or prevent its formation. The object of this paper is to present the results of a number of records recently secured from autographic meteorological instruments mounted on airplanes at times when ice formed.

Ice is found to collect on an airplane in appreciable amounts only when the airplane is in some form of visible moisture, such as cloud, fog, mist, rain, etc., and the air temperature is within certain critical limits.

There are two principal types of ice formation that collect under such conditions, and in view of the different effects of each of these on a plane they will be discussed separately under their respective headings, viz., clear ice and rime.

Clear ice.- This is the same type as that commonly known as "glaze," which forms on the ground, trees, and other objects from rain when the temperature of these objects is below 0°C. It usually is smooth and glassy in appearance, but when mixed with snow or sleet it may be rough; also, when freezing takes place slowly, ridges are likely to form.

This deposit usually is heaviest on the entering edge of the plane where it assumes a blunt-nosed shape tapering off toward the rear. Occasionally the wings are ice-coated on both top and bottom with icicles along the trailing edge. In most cases the ice adheres firmly to the surface of the airplane.

Rime.- Rime consists of hard, whitish, opaque ice pellets or grains, frequently intermixed with a frost formation of light feathery crystalline structure. From observations of rime deposits on mountains, Köhler (reference 1) described the formation as snow-white, plug-like, truncated cones with the small end toward the surface upon which it is deposited. The plugs showed a fibrous structure and occasionally shiny surfaces. The particles from which the plugs were composed were firmly held together but the plugs themselves could easily be separated from one another. Their interior was usually of granular appearance. The spaces between the plugs were filled with a powder composed of these grains. From laboratory tests by Scott (reference 2) the granular structure of rime appeared to be coarsor at the lower temperatures of formation.

Unlike clear ice, rime builds outward from the leading edges of the airplane into a sharp-nosed shape. As a rule it does not adhere to the plane as firmly as clear ice and is less resistant to the vibration and wind force encountered in flight.

Frost.- A third type of deposit of lesser importance, however, than clear ice and rime, which sometimes forms on airplanes is frost. This is of a light feathery crystalline structure such as often is observed on ground objects in the early morning. It does not adhere to the airplane very firmly and is never dangerous as it has very little resistance to the vibration and wind force encountered in flight.

Effects of ice deposit.- As a rule the first noticeable effect of an ice deposit is an increase in vibration of the airplane followed by increasing difficulty in its control. As the deposit becomes heavier the vibrations may cause severe structural strains with a possibility of fracturing individual parts. The deposit frequently stops up the nozzle of the air-speed indicator thus rendering that instrument useless. Other instruments may also be affected. An ice formation on the propeller is likely to produce a difference in weight of the blades which may become sufficient to cause the engine to break loose. Forced landings frequently are necessary due to icing.

The chief dangers to lighter-than-air craft result from the ice being thrown off the propeller and possibly puncturing the gas containers. Also, the distribution of the ice on the airship may cause structural strains with

the possible collapse of a nonrigid or semirigid type. Ice collections on the radio antennae may result in their breaking. In general, however, ice deposits on lighter-than-air craft are less serious in their effects than on airplanes. (Reference 3.)

A deposit of clear ice is a greater hazard to an airplane in flight than one of rime. The reason for this is that clear ice formations, by virtue of their blunt-nosed shape, break up the normal air flow over the surface of the airplane and thereby reduce the lift, increase the friction, and cause excessive vibration. The weight of the ice also adds to the danger, although this factor in itself usually is of less importance. On the other hand, the contours formed by rime produce less detrimental aerodynamical effects, and moreover, rime is much more easily blown and shaken off the airplane.

Results of observations.- The records obtained by the Weather Bureau, previously referred to, were classified according to the two general types of formation, viz., clear ice and rime, together with the respective temperatures, relative humidities, clouds, and elevations above ground at which the formations occurred. This classification includes 108 cases where rime formed, 43 cases in which clear ice formed, and 4 cases when both rime and clear ice formed during the same flight. It is evident from the above figures that there was a preponderance of rime by the ratio of 2.5 to 1, while in only a very few cases both types of ice formation occurred during the same flight.

Table II contains a summary of the observations shown in Table I. In examining these tables, it should be kept in mind that the airplane usually continued to climb after ice began to form and therefore the temperature was generally lower where the formation ceased than where it began. Also, the heavier coatings are in most cases a consequence of the airplane being subjected to ice-forming conditions for a longer time than when the lighter coatings formed.

The following points of interest are brought out in Table II:

1. The temperature averaged 1.8°C. lower during the rime formations than during those of clear ice.

2. The average temperature interval, i.e., range of temperature from beginning to end of formation, for rime and clear ice was the same, viz., 3.1°C.

3. The relative humidity averaged practically the same during the rime formations as during those of clear ice. In this connection it should be stated that owing to the fact that the airplane usually was climbing while the ice formed, the resulting lag in the humidity element would tend to indicate values somewhat too low, particularly at the lower part of the stratum wherein the ice formed. However, it is reasonable to assume that unsaturated conditions frequently obtain within clouds since tabulations by Pick (reference 4) show that fogs often occur with a relative humidity of less than 100 per cent.

4. The average relative humidity interval, i.e., the range of humidity from beginning to end of formation, was practically the same for rime and clear ice, the humidity being about 2 per cent higher at the end of the formation than at the beginning. This difference is probably due to a large extent to the lag mentioned above in paragraph 3.

5. The average time interval during which the formations occurred was only slightly greater for clear ice than for rime, viz., 6.3 and 6.1 minutes, respectively.

6. The average elevations at which rime formed were somewhat higher than those for clear ice, with the exception of the heaviest coatings, in which case the clear ice formations occurred at a greater average height than those of rime.

7. The average thickness of the stratum in which the formation occurred was somewhat greater for clear ice than for rime.

8. The fact that clear ice has, in general, a more serious effect than rime is well brought out by the following figures which give the percentage of flights listed in Table I which were terminated because of ice formation.

	Terminated because of ice formation	Thickness of ice
Clear ice	31 per cent	1/4 inch or more
Clear ice	12 "	Less than 1/4 inch
Rime	4 "	1/4 inch or more
Rime	0 "	Less than 1/4 inch

In Figure 1 are shown the actual number of cases when each of the two types of ice formation occurred at various temperatures, the latter representing the mean of the temperature range through which the formation occurred.

Probably the most outstanding feature shown by this chart is the fact that rime formed more frequently than clear ice at <u>all</u> temperatures. From this it is obvious that temperature alone cannot be used as a safe criterion for indicating which type of formation will occur on any particular occasion.

Additional features shown are:

1) The temperatures at which the most frequent deposits occurred were higher for clear ice (-4°C. to -5°C.) than for rime (-6°C. to -7°C.). These values agree closely with those found by Peppler (reference 5) from kite observations. The latter indicated that clear ice formed at an average temperature of -4°C. and rime at -6°C.

2) The extreme temperature range during clear ice deposits (0.5°C. to -17.5°C.) was slightly less than that for rime (0.5°C. to -20.5°C.).

In this connection it is interesting to note that Köhler (reference 1) observed a thin layer of clear ice which formed from a "wet fog" at -23.6°C.

In Figure 2 are shown the percentage frequencies of clear ice and rime formations at various temperatures, the latter, as in Figure 1, representing the mean of the temperature range through which the formation occurred. It should be understood that the percentages indicated in Figure 2, as well as those in Figures 3, 4, and 5 are with reference to the total number of each of the respective types and not to the total number of both types.

A significant feature shown in this chart is the tendency for clear ice to form at relatively higher temperatures a greater percentage of the time than rime. By computation it is found that 58 per cent of the total number of clear ice formations occurred at temperatures at, or above, -5°C., whereas only 37 per cent of the total number of rime formations occurred at those temperatures.

Figure 3 shows the percentage frequencies of both types of formation at the temperatures at which the ice <u>began</u> to form.

It is evident from this chart that the clear ice formations began most frequently at a slightly higher temperature (0°C.) than those of rime (-2°C.). Both types began forming at the same maximum temperature (1°C.). Rime began forming at a lower temperature (-20°C.) than clear ice (-17°C.). By computation it is found that in 74 per cent of the total number of clear-ice deposits the temperature at the beginning of the formation was -5°C., or higher, as compared to only 55 per cent in the case of rime.

Since, as previously pointed out, both clear ice and rime may form over practically the same range of temperature it is necessary to conclude that one or more other factors are decisive in determining which type is deposited. We may also conclude that the other decisive factors just referred to change in their potency or relative frequency with temperature, so that the factors favoring the formation of clear ice, for example, are more frequent or more powerful, or both, at higher temperatures than at lower temperatures.

In Figure 4 are shown the percentage frequencies of clear ice and rime formations at various heights above the ground, the latter representing the mean of the height interval in which the formations occurred. The following features are evident in this chart:

1) A very pronounced maximum frequency of occurrence of both clear ice and rime at relatively low heights, viz., between 500 and 1,000 m (1,640 and 3,281 ft.).

2) Pronounced secondary maximum frequencies of occurrence between 2,500 and 3,000 m (8,200 and 9,842 ft.) for clear ice and between 4,000 and 4,500 m (13,123 and 14,764 ft.) for rime. These primary and secondary maximum frequencies of occurrence are possibly related to layers of maximum condensation. Such a layer was found by Lewis (reference 6) between 500 and 1,000 m (1,640 and 3,281 ft.) above ground where the maximum frequency of strato-cumulus cloud bases occurred.

3) Low frequencies of occurrence of both types of ice formation between 1,500 and 2,500 m (4,920 and 8,200 ft.) above ground.

4) Both types of formation occurred throughout the same strata and with small and practically equal percentages of frequency at the lowest and greatest heights

reached. The maximum heights where icing occurred coincide with the maximum heights of the flights.

In Figure 5 are shown the percentage frequencies of both types of ice formation for various cloud and weather conditions. The following features are brought out:

1) Both clear ice and rime formed most frequently in strato-cumulus clouds.

2) When in rain but not in cloud, the formation was always clear ice, whereas when in rain and cloud, the formation was sometimes rime and sometimes clear ice.

3) When above cloud and not in any form of precipitation, the formation was always clear ice. In such cases the deposit formed from moisture collected on the airplane while passing through the cloud.

4) Comparatively high percentage frequencies of clear-ice formations occurred in alto-stratus clouds and of rime in stratus clouds.

5) No ice deposits were reported in cumulus clouds. This is doubtless due to the fact that most of the observations were made before daylight (about 5 a.m., 75th meridian time), when cumulus clouds are seldom present.

An examination of the prevailing temperature lapse rates occurring in these observations showed no relationship between the lapse rates and the types of ice formation.

The relative distribution of the number of occurrences of both types of formation from the data at hand is shown in Table III. It will be noted therein that the ratios of rime and clear ice deposits vary considerably for the four stations. As was previously stated this ratio for the observations for all stations combined was 2.5 to 1, with a preponderance of rime. However, these ratios for the individual stations are as follows: Chicago, 1.7; Cleveland, 7.5; Dallas, 5.5; and Omaha, 0.6. It is also found that the ratios between the light and heavy deposits vary considerably among the individual stations, e.g., the heavy coatings of clear ice predominate at Chicago and Cleveland, whereas the light coatings of clear ice predominate at Omaha and apparently at Dallas. The heavy coatings of rime predominate at Cleveland and apparently at Dallas, whereas the light coatings of rime predominate at Chicago and Omaha.

Cleveland had the greatest number of rime formations, with Chicago second, Dallas third, and Omaha fourth. This same order, however, did not occur in the case of clear ice. While this may be partly due to the smaller number of observations of this type, it is probably due also in part to other factors such as available nuclei and prevailing winds with respect to nearby water areas.

It is shown in Table IV that the average temperature was lower during the rime formations than during those of clear ice at every station.

A comparison of the ratios of the total number of cases of both types of ice deposits to the average amount of lower clouds reveals no proportionality. (See Tables III and IV.) The average heights where the formations occurred were approximately the same as the average heights of strato-cumulus (i.e., lower) clouds in which the maximum number of formations occurred. (See Table II.) Therefore other conditions than the incidence of clouds at subfreezing temperatures must be sought as controlling factors. A possibility in this connection is the relative number of available nuclei as a factor in the determination of the size of the cloud droplets.

A comparison of the average temperatures during the ice formations (Table IV) with the average for the season at corresponding heights shows lower temperatures during the times of formation with one exception, viz., Cleveland, for clear ice. This station had relatively few cases of clear ice deposits and it seems probable that this relatively high average temperature at the time of formation is due to the proximity of Lake Erie and the prevailing winds which were mostly off the lake at those times. Greater temperature differences will be noted in the case of rime than for clear ice at all stations.

<u>Factors bearing on the type of ice formation</u>.- It has been shown that other factors than temperature have an important bearing on the nature of the ice deposit, i.e., clear ice or rime. One of these factors presumably is the size of the water droplets. It seems probable that, in general, large droplets tend to form clear ice, whereas small droplets usually produce rime. This view is strengthened by the fact that the deposit formed while flying in rain, i.e., when not encountered with cloud particles, is always of the clear ice type. Köhler (reference 1) came to the conclusion that when a sufficient number of large un-

dercooled droplets impinge on a suitable object, the freezing of a portion of the water deposited liberates latent heat of fusion which, if not conducted away with sufficient rapidity, causes the temperature of the deposit to rise, possibly as high as 0°C. This permits the spreading and flowing of the water droplets referred to above and a layer of liquid admixed with some ice results. By virtue of this higher temperature the saturation vapor pressure over the deposit will now be higher than the vapor pressure about the subcooled droplets in the cloud and evaporation will occur and hence a cooling of the deposit, an effect which under the conditions given above, when combined with the loss of heat by conduction to the passing air stream and to objects upon which the water is deposited produces freezing of the remaining liquid and gives rise to clear ice.

On the other hand, small droplets are more likely to freeze immediately upon striking the airplane. This is in part due to the greater convexity and different distribution of mass and cohesive forces in smaller droplets, all of which hinder them from spreading and flowing and aid in maintaining their spherical form. Since there is a greater exposed surface area about a given mass of water in the form of small droplets than about an equal mass which has spread and flowed from larger droplets, the removal of the latent heat of fusion liberated is probably more rapid in the former case. Hence, in general, small droplets have a greater speed of crystallization than have large droplets, a condition which, in the opinion of Köhler (reference 7), is conducive to the formation of rime.

It seems probable, however, that small droplets might also produce clear ice where the circumstances are such that the liberated heat of fusion is not conducted away with sufficient rapidity.

Köhler thought it probable that the type of ice formation depends to a considerable extent upon the speed of crystallization at which the liquid water freezes, there being a critical value for this speed which, when exceeded, produces rime or frost and when unattained produces clear ice. He thought it possible also that a higher critical value of the speed in question might exist which, when exceeded, produced frost instead of rime.

The speed of crystallization, in turn, depends on the degree of concentration of the dissolved salts serving as nuclei and on the temperature of the subcooled droplets.

(Reference 7.) Thus for a given concentration and a relatively low temperature the speed of crystallization is relatively high, whereas, for the same concentration at a relatively high temperature the speed of crystallization is relatively low. Also, for a given temperature and a low concentration the speed of crystallization is relatively high, whereas, at the same temperature and a high concentration the speed of crystallization is relatively low.

From measurements of the concentration of salts in clear ice and rime deposits and the corresponding sizes of fog and cloud droplets on mountains in Europe, together with certain assumptions, Köhler (reference 7) concludes that the sizes of droplets in clouds, from which no precipitation is falling and which exist simultaneously at the same elevation, depend on the respective sizes of the salt particles about which condensation has occurred. His calculations show that high concentrations are associated with small droplets and, vice versa.

It will be noted that it was stated above that small droplets are associated with a high concentration of salt nuclei, that the latter produces a relatively low speed of crystallization and further, that the latter generally tends to produce clear ice. From other considerations it was concluded that small droplets generally tend to form rime. Thus we find from two sets of considerations that small droplets tend to form both clear ice and rime. It must therefore be concluded that further investigation of this phase of the subject is necessary in order to determine qualitatively and quantitatively the manner in which the various factors operate to produce the particular type of ice deposit. A parallel line of reasoning applies to large droplets.

Another possible factor bearing on the type of ice deposit is the mass of water striking a unit area in unit time. (Reference 7.) It is obvious that the mass of water in question depends on the amount of water per unit volume of the cloud and on the speed of the airplane. When the mass of water striking a unit area in unit time is large a sufficient amount of latent heat may be liberated so as to produce clear ice in the manner previously described.

Scott found from wind-tunnel experiments that the air speed apparently has little effect upon the character

of the ice formation. (Reference 2.)

The formation of frost on aircraft, previously referred to, is a result of sublimation, i.e., a change directly from the gaseous to the solid state, and therefore requires a state of supersaturation with respect to ice.

Sudden ice deposits.- It has been suggested by various authors that supersaturation, with respect to ice, in clouds composed of subcooled water droplets may be responsible for comparatively sudden and heavy deposits occasionally reported by pilots. Humphreys (reference 8) has shown, however, that at a temperature of -10°C., if all of the excess vapor in the air, i.e., assuming a condition of supersaturation with respect to ice, were deposited, it would be equivalent to a layer of clear ice one inch thick on the front of an airplane after the latter had flown for a distance of 72 miles. It is probable though that only a small part of the excess vapor encountered would be deposited on the airplane

An occurrence of a sudden deposit together with a possible explanation was recently reported by A. Hansen. (Reference 9.) The following is quoted therefrom.*

"In a summer cumulus cloud with strong heat convection, the speed indicator stopped functioning almost immediately because of icing of the nozzle upon flying into the cloud. The bumpiness was such that the airplane did not respond to the movements of the rudder. After 5 or 10 seconds the corrugated ribs on the top side of the wing were concealed under a layer of ice, which had not thickened on the front edges, but the entire visible wing surface was apparently equally heavily coated. The thermometer showed about 0°C., the air was very wet, the height was about 3,600 m (11,811 ft.). In consequence of the excessive demands, the airplane quickly lost altitude in spite of the thermal convection and wide-open engine and soon fell out of the cloud base. Here the ice melted quickly and at about 1,000 m (3,281 ft.) had completely disappeared.

"The suddenness of the icing and the unusual form of the ice cover even in the region of dynamic pressure reduction cannot be explained in the usual manner. It seems

*Translated by J. C. Ballard, Aerological Division, Weather Bureau.

plausible that here the "triple point"* plays a part. If the vapor pressures over water and ice are equal, the heat of vaporization and heat of fusion may be exchanged for one another in the presence of liquid water. Since the process is intermolecular and no external heat exchange is assumed, it can take place practically instantaneously. Since the heat of vaporization is about eight times as great as the heat of fusion, a partial evaporation must form an eightfold quantity of ice. The vaporization can be caused by dynamic pressure reduction on the airplane; for example, on the top side of the wing. Through consideration of the triple point, the manner and speed of this special type of icing follow quite naturally."

In connection with the foregoing, it is interesting to note in Table I that in most cases where rapid icing occurred the temperature was not much below the freezing point, and it seems possible that the physical explanation of at least a part of the ice formation in those cases is similar to that given by Hansen.

In general, no ice formation will occur at temperatures above freezing. However, occasionally cases are reported where it does form in wet clouds or in rain at temperatures slightly above freezing, and in such cases it is probable that the ice is formed by evaporative cooling, the extent of which varies inversely as the relative humidity.

<u>Undercooled water droplets</u>.- In connection with the occurrence of undercooled cloud droplets, it is of interest to note that these are found at surprisingly low temperatures. A. Wegener (reference 10) observed a "fog-bow" in Greenland at a temperature of -34°C., indicating that the fog particles were in the liquid state.

At Little America, headquarters of the Byrd Antarctic Expedition, both cloud and fog particles were frequently observed in the liquid state at very low temperatures. W. C. Haines (reference 11), meteorologist of this expedition, states as follows regarding this:

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*The triple point is the temperature (0.0072°C.) and vapor pressure (4.58 mm of mercury) for which the three states - vapor, liquid, and solid - can exist together in equilibrium. At the triple point the saturated vapor pressures for ice and water are identical.

"Fog, while infrequent, was interesting from the point of view of showing that water particles can, and do, exist in the atmosphere at temperatures far below the freezing point. Considerable attention was given by Mr. Henry T. Harrison and myself in observing this phenomenon. We used great care in examining fog or mist when it occurred before recording it as such. In every case when the fog was dense and lasted for an appreciable length of time, a deposit of rime would form on the windward side of objects due to the impingement of the undercooled fog particles. Fogs were observed at temperatures of -26°C., -30°C., and -44°C.

"During kite flights at Little America, when clouds of the stratus or strato-cumulus type were entered, the kites and wire would always be covered with rime on reeling in, thus proving beyond doubt that the clouds were composed of water particles. The lowest temperature observed at the cloud base was approximately -18°C. However, these clouds had the same appearance as those of similar type observed at -45°C., or -50°C. Who can say definitely but that they also were composed of water particles?"

The complete explanation of the manner in which water exists in the liquid state at such low temperatures is not known. Köhler (reference 7), from his investigation of the solid substances found in rime, ice, and snow, is of the opinion that this is primarily due to the concentration of salts dissolved in the droplets. While Köhler is inclined to believe that sea salt is the chief source of these nuclei, Lenard and Ramsauer (reference 12) have shown that the effects of ultra-violet solar radiation upon certain atmospheric constituents may produce hygroscopic nuclei of composition different from that of sea salts and equally, or more effective in respect to their hygroscopic properties. Such substances dissolved in the droplets would have the same effect as regards subcooling as sea-salt nuclei. Solutions of any of these substances may be cooled to various temperatures below 0°C., before freezing occurs, depending on the concentration and kind of substance, the degree of ionization, the radius of the droplets and possibly, also, on other factors.

<u>Other conditions favorable or unfavorable to ice formation</u>:- A deposit of frost may occur when an airplane descends rapidly from a region where the temperature is below freezing into a warmer, but still subfreezing stratum,

which is nearly or entirely saturated. In such a case the formation occurs instantly but stops as soon as the airplane attains the same temperature as that of the surrounding air.

Another condition conducive to frost is in air nearly saturated and the temperature at, or below freezing. The reduced air pressure, and consequently lowered temperature, just above the wings in such a region might be such that condensation would cause a small amount of frost to form.

Sleet, by itself, does not collect on an airplane. However, when mixed with rain it is likely to form a rough and dangerous coating.

Clouds composed of ice spicules do not form any appreciable deposit.

Dry snow does not adhere to an airplane. A mixture of snow and rain or cloud droplets, however, is likely to form a dangerous deposit of frozen slush.

Ice deposits from freezing rain may often be partially removed or prevented by flying in the inversion, i.e., warmer layer, which usually exists above such rains.

A light deposit may form on an airplane flying in a region where cloud droplets are of such small size as to render them invisible, providing the temperature is below freezing.

Methods of determining whether ice will form.- The fact that ice deposits of appreciable amounts do not occur unless the airplane is in some form of visible moisture, is of prime importance because in this way the pilot is visually warned, providing he knows the air temperature. The latter can be ascertained by means of a distant indicating thermometer. At night visible moisture can generally be detected by means of a light on the airplane.

In view of the important difference in the effects of clear ice and rime formations on an airplane in flight, it is obvious that any means of determining which of the two types is likely to form on any particular occasion would be of great benefit. While temperature cannot be used as a sole criterion in regard to the particular type of ice formation it is, however, the principal criterion as regards the probability of any formation at all. With-

out upper air observations the temperature aloft must, of course, be estimated from surface conditions. To do this properly one must assume a certain lapse rate, i.e., vertical change in temperature. The lapse rate prevailing at any particular time depends on a variety of factors, the principal ones being (a) time of day, (b) season, (c) latitude, (d) nature of the surface, i.e., land or water, (e) cloudiness, (f) wind velocity and direction, (g) atmospheric pressure distribution, and (h) precipitation. As many of these factors as possible should be taken into consideration.

The following will assist in estimating the temperature lapse rate at any particular time.

On the average the temperature decreases about 0.6°C. per 100 m (328 ft.) elevation. In the lower levels, i.e., the first 1,000 m (3,281 ft.) or so, the lapse rate may vary from slightly more than 1°C. per 100 meters to a large negative value, i.e., the temperature may <u>increase</u> with elevation. The latter condition is called a temperature inversion and is a common phenomenon at night and early morning during clear, calm weather. It is most pronounced in winter and at higher latitudes. A solid cloud layer at night tends to minimize the intensity of the nocturnal inversion, as then terrestrial loss of temperature is materially reduced by the return radiation from the cloud. The intensity of nocturnal inversions is likewise reduced by wind which mixes the air and thereby prevents extreme stratification.

During mid-afternoon, particularly in the warmer season, the lapse rate generally increases until it reaches, or slightly exceeds, the adiabatic rate for dry air, i.e., 1°C. per 100 meters. An overcast sky during the daytime tends to keep the lapse rate low, as then the clouds intercept a large part of the solar radiation by absorption and reflection.

Precipitation tends to decrease the lapse rate. The lapse rate within a cloud is usually less than in clear air, except that immediately above sheet clouds there is often a temperature inversion.

For more detailed information regarding the effects of these and other factors bearing on the temperature lapse rate reference should be made to a good textbook on meteorology.

The determination of the size of cloud droplets from ground observations is difficult. An incipient rain condition is a fairly certain indication of large droplets. This may be indicated by the appearance of the clouds and a knowledge of general weather conditions at surrounding stations.

Some indication of the size of cloud droplets is afforded by the presence of a corona which, if very close to the sun, or moon, signifies relatively large droplets, whereas, when the corona is large, i.e., farther away from the sun, or moon, the droplets are correspondingly smaller. This criterion, however, would probably be of little practical value, since coronae are visible only when the clouds are thin and under such conditions the danger of icing usually is not serious.

The presence of a halo indicates clouds composed of ice spicules which, as previously stated, do not form any appreciable ice deposit.

Low pressure areas usually are more favorable for icing conditions than high-pressure areas, since the former are generally attended by considerable cloudiness and precipitation. Favorable icing conditions are likely to obtain in regions to the leeward of large bodies of water where temperatures of freezing, or lower, frequently occur; also over high terrain where flights at high elevations are necessary.

In closing, it is desired to state that one of the chief difficulties in a study of this kind is the frequent impossibility for the pilot or observer to classify correctly the type of ice formation since it usually is melted by the time the airplane reaches the ground. Since many of these flights were made before daylight this difficulty was especially pronounced. Also, there is a certain amount of confusion in the minds of many as to what constitutes rime and what clear ice. It is hoped that the descriptions given here will make possible a more accurate classification in this respect in future observations. It is believed, however, that so far as averages are concerned, the values found would not change appreciably with additional observational data.

It is desired to acknowledge the cooperation of the National Air Transport, Inc., Chicago, Ill., with the

Weather Bureau in the procurement of a number of airplane observations during ice-forming conditions. During the winters of 1928-29 and 1929-30, regular mail planes flying between Chicago and New York and between Chicago and Kansas City, were equipped with aero-meteorographs when conditions appeared favorable for ice formation. Local flights such as are now made daily at the Weather Bureau airport stations at Atlanta, Ga., Chicago, Ill., Cleveland, Ohio, Dallas, Texas, and Omaha, Nebr., however, provide far more satisfactory data for a study of this kind than do flights made over great horizontal distances.

I am indebted to Mr. L. P. Harrison of the Aerological Division, Weather Bureau, for many helpful suggestions during the preparation of this paper.

Weather Bureau,
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*A paper by W. Bleeker, entitled "Einige Bemerkungen über Eisansatz an Flugzeugen," Met. Zeit., Bd. 49, Heft 9, 1932, pp. 349-354, came to the attention of the author after the completion of this paper. Bleeker emphasizes the effect of evaporative cooling in the freezing of water droplets; also the time required for a drop to freeze ("Vereisungszeit") is considered to be proportional to the radius of the drop and thus a factor in determining the amount of deposit. Applications of the above, computations based thereon, and other topics are also discussed.

TABLE I. FLIGHT OBSERVATIONS MADE DURING THE FORMATION OF ICE ON THE AIRPLANE, CLASSIFIED ACCORDING TO THE TYPE AND THICKNESS OF FORMATION

Cloud or other conditions in which ice formed	Elevation above ground where ice began to form	Elevation above ground where ice ceased to form	Temperature where ice began to form	Temperature where ice ceased to form	Relative humidity where ice began to form	Relative humidity where ice ceased to form	Time interval in which ice formed	Thickness of coating	Parts of airplane where ice formed	Remarks	Place and date of observation
	Meters	Meters	°C	°C	Per-cent	Per-cent	min.	in.			
									CLEAR ICE, 1/4 INCH OR MORE		
St.	250	590	0	- 1	95	95	3 1/2	1/2	Wings, wires and struts		Cleveland, Jan. 3, 1932
A.-St.	1,900	2,060	- 5	- 6	91	89	3	1/4	All leading edges	Smooth	Chicago, Jan. 2, 1932
A.-St.	3,100	3,950	+ 1	- 3	95	95	14	1/4	Wire, struts and trailing edges of wings	Very clear and rather rough, snowing from these clouds	Chicago, Nov. 20, 1931
A.-St.	2,640	2,970	- 3	- 5	98	98	7	1/2	All leading edges	Forced to descend because of ice formation	Chicago, Feb. 21, 1932
St.-Cu.	900	1,420	- 7	-10	84	90	5	1/2	Propeller, wings, wires and struts	Rough, 1/2 in. on wires, 1/4 in. on wings	Cleveland, Feb. 24, 1932
St.-Cu.	420	990	0	- 2	91	91	6	1/4	Leading edges all exposed surfaces	Flaky	Chicago, Jan. 27, 1932
St.-Cu.	2,380	2,860	- 4	- 7	91	99	9	1/2	Leading edges all exposed surfaces	Sufficient to cause end of flight	Chicago, Jan. 5, 1932
St.-Cu. and rain	3,100	3,500	0	- 2	91	91	1 1/2	1/4	Wings, wires and struts		Cleveland, Jan. 17, 1932
St.	550	1,040	0	- 3	90	98	4	1/2	All leading edges	Rough	Omaha, Mar. 4, 1932
St.-Cu.	3,600	4,560	- 7	-23	90	87	24	1/4	Leading edges, all exposed parts	Smooth, ice on wings made further climb impossible	Omaha, Mar. 18, 1932
St.-Cu.	4,140	4,460	-12	-15	90	93	4	1/4	Leading edges, all exposed parts	Smooth. Airplane became so heavy with ice that it began to lose altitude and further climb impossible	Omaha, Mar. 19, 1932
St.-Cu.	850	1,370	- 9	-10	90	90	3	1/4	Leading edges, all exposed parts		Chicago, Mar. 22, 1932
A.-St.	1,420	1,900	- 5	- 8	85	94	—	1/4	Wings, wires, struts and tail surfaces		Chicago, Mar. 24, 1932
A.-St. and rain	3,870	4,370	- 2	- 8	95	98	13	1/4	Leading edges		Chicago, Apr. 24, 1932
A.-St.	4,450	4,640	-14	-17	78	80	13	1/4	Leading edges		Chicago, Apr. 25, 1932
St.-Cu.	1,270	1,630	- 5	- 8	78	85	6	1/2	Leading edges and propeller	Airplane vibrated and flight had to be abandoned	Chicago, Apr. 26, 1932
St.-Cu. and mist	2,380	3,110	- 1	- 5	95	95	8	1/2	Wings, wires and struts	Rough, 1/2 in. on wires and struts, 1/4 in. on wings	Cleveland, May 31, 1932
A.-St. and rain	3,500	3,930	- 1	- 5	98	94	8	3/8	Wings, wires and struts	Rough	Cleveland, June 1, 1932
A.-St.	3,070	3,400	- 2	- 4	99	98	4	1/2	Wings, wires and struts	Rough, flight stopped because of ice	Cleveland, May 14, 1932
									CLEAR ICE, LESS THAN 1/4 INCH		
A.-St.	2,859	2,890	- 2	—	100	—	1	1/8	Wires and struts	Rough	Cleveland, May 4, 1932
St.-Cu.	1,100	3,360	0	- 9	98	96	15	1/8	Leading edges, struts and windshield	Smooth, airplane became so heavy with ice that pilot was unable to climb higher, much ice remained on airplane after landing	Omaha, Apr. 26, 1932
St.-Cu.	1,250	1,380	- 7	- 8	85	87	1	Thin	On aero-meteorograph and various parts of airplane		Chicago, Mar. 17, 1932
St.-Cu.	730	1,250	- 4	- 6	84	88	3	Thin	On aero-meteorograph and leading edges		Omaha, Mar. 30, 1932
St.-Cu.	1,350	2,860	- 2	- 8	96	97	7	1/8	Leading edges and struts	Airplane seemed heavy at top of clouds	Omaha, Jan. 4, 1932
St.-Cu.	770	830	- 7	- 9	95	85	8	Thin	Leading edges of wings		Omaha, Jan. 5, 1932
St.-Cu.	1,170 570	1,380 1,340	- 5	- 8	86	94	2 1/2	1/8	Leading edges of wings	Hard crystalline ice, made very noticeable difference in the handling of airplane	Omaha, Dec. 5, 1931
St.-Cu.	750	1,090	- 5	- 5	97	98	5	1/8	Leading edges of wings	Prevented further ascent	Omaha, Dec. 13, 1931
A.-St.	4,930	5,170	-17	-18	70	80	1	Thin	Windshield	Hard crystal, smooth	Omaha, Nov. 21, 1931
A.-St. and A.-Cu.	3,190	3,250	-16	-18	86	90	3	Small amount	Windshield and leading edges		Omaha, Dec. 13, 1931
St.	3,530 1,330	3,640 2,220	- 4	- 8	88	96	5	1/32	Leading edges of wings, struts and aero-meteorograph	Smooth, very noticeable as wires began to scream	Omaha, Feb. 1, 1932
St.	950	1,180	- 1	- 2	95	96	1	Thin	Struts and wings	Streaked in very thin patches	Chicago, Dec. 29, 1931
St.	840	1,130	- 4	- 6	90	93	2		Windshield	Probably clear ice but insufficient to determine definitely	Omaha, Nov. 27, 1931
Above St.	1,300		- 1	—	90	—	—	Small amount	Wings, wires and struts	Moisture carried from clouds froze after emerging from clouds, frozen in drops	Cleveland, Oct. 31, 1931
Mist (below St.-Cu.)	1,100		- 3	—	84	—	—	Thin	Struts	Smooth, none formed in clouds	Omaha, Oct. 29, 1931
Above St.-Cu.	900		+ 1	?	85	—	—	Small amount	Trailing edge of struts, wings and on windshield	Formed from moisture left on airplane from clouds	Chicago, Oct. 31, 1931
Above St.-Cu.	4,150		- 1	?	83	—	—	Thin sheet	Trailing edge of wings	Formed from moisture left on airplane from clouds	Dallas, May 29, 1932

Meters x 3.28083 = feet

TABLE I. (Cont) FLIGHT OBSERVATIONS MADE DURING THE FORMATION OF ICE ON THE AIRPLANE, CLASSIFIED ACCORDING TO THE TYPE AND THICKNESS OF FORMATION

Cloud or other conditions in which ice formed	Elevation above ground where ice began to form	Elevation above ground where ice ceased to form	Temperature where ice began to form	Temperature where ice ceased to form	Relative humidity where ice began to form	Relative humidity where ice ceased to form	Time interval in which ice formed	Thickness of coating	Parts of airplane where ice formed	Remarks	Place and date of observation
	Meters	Meters	°C	°C	Per-cent	Per-cent	min.	in.	RIME, 1/4 INCH OR MORE		
St.-Cu.	1,380	1,680	- 1	- 3	96	98	3	5/16	Wings, wires and struts	Rough	Cleveland, May 28, 1932
St.-Cu.	1,300	1,600	- 4	- 7	85	93	3	1/4	Wings, wires and struts	Frosty white	Cleveland, Jan. 27, 1932
St.-Cu.	730	990	- 5	- 8	92	96	4	1/4	Leading edges, struts and aerometeorograph		Chicago, Dec. 5, 1931
St.-Cu.	2,350	3,010	0	- 5	90	94	8	3/8	All surfaces		Chicago, Feb. 16, 1932
A.-Cu.	3,680	4,000	- 5	- 7	85	96	28	3/4	1/2 in. on wire, 3/4 in. on leading edges and wings	Airplane suddenly stopped climbing due to ice, very rough and white	Chicago, Dec. 22, 1931
A.-Cu.	4,150	4,830	-10	-14	83	93	35	—	All over wings, struts and rigging	Unable to climb higher due to ice	Dallas, Dec. 30, 1931
A.-Cu.	3,480	3,710	-18	-13	75	86	10	3/8	All surfaces including under side of wings	Could not climb higher due to ice	Chicago, Feb. 9, 1932
A.-St.	3,270	3,870	0	- 2	95	95	4	—	Noticed on shield only	Probably formed on wings also as airplane became very unmanageable	Omaha, Oct. 12, 1931
A.-St.	3,390	3,700	+ 1	0	92	94	6	1/4	Wires and struts	Frosty white	Cleveland, Nov. 12, 1931
A.-St.	1,850	2,850	- 5	- 8	95	96	5	1/4	Wings, wires and struts		Cleveland, Dec. 6, 1931
A.-St.	2,100	2,400	+ 1	- 1	95	96	3	1/4	Wings, wires and struts		Cleveland, Dec. 9, 1931
A.-St.	3,850	4,090	-10	-14	92	90	18	1/4	Wings, wires, struts and propeller		Cleveland, Jan. 5, 1932
	4,380	4,590									
St.	840	1,070	- 6	- 9	86	92	3 1/2	1/4	Wings, wires and struts		Cleveland, Jan. 25, 1932
St.	640	1,190	- 6	-10	90	98	5 1/2	3/8	Wings, wires and struts		Cleveland, Jan. 30, 1932
St.	860	1,190	- 4	- 6	95	97	4 1/2	1/2*	(More than)* Wings, wires and struts		Cleveland, Dec. 25, 1931
St.	880	1,130	- 5	- 9	96	100	5	1/4	Wings, wires and struts		Cleveland, Dec. 15, 1931
St.	880	940	- 2	- 4	96	100	2	1/2	Wings, wires and struts	Ice formed rapidly and came off as soon as I got under base of clouds	Cleveland, Dec. 14, 1931
St.	960	1,120	- 7	- 8	96	98	6	1/2	Wings, wires and struts		Cleveland, Dec. 5, 1931
St.	460	1,020	0	- 2	90	93	4	3/8	Wings, wires and struts		Cleveland, Nov. 30, 1931
St.	500	940	- 2	- 4	89	93	2	1/4	Wings, wires and struts	Evaporated quickly in the clear air	Cleveland, Nov. 29, 1931
St.	670	1,470	- 6	- 8	80	85	2	1/4	Wings, wires and struts		Cleveland, Nov. 25, 1931
St.	660	980	- 3	- 5	98	100	2 1/2	1/4	Wings, wires and struts		Cleveland, Feb. 3, 1932
St.-Cu. rain and sleet	3,450	4,840	- 2	-10	93	90	28	*	Leading edges wings and struts	*Rigging coated to twice normal size	Dallas, Nov. 29, 1931
St.-Cu. and rain	3,090	3,630	0	- 2	96	98	10	1/2	Leading edges wings and struts		Dallas, Jan. 4, 1932
St.-Cu. and snow	640	1,130	-10	-12	86	86	3	1/4	Wings, wires and struts		Cleveland, Feb. 18, 1932
St.-Cu. and snow	680	1,800	-10	-20	86	90	10	1/4	Wings, wires and struts		Cleveland, Feb. 23, 1932
St. and snow	980	1,760	- 5	-10	90	90	7	3/8	Leading edges wings, wires and struts		Cleveland, Dec. 1, 1931
St. and rain	1,260	1,820	0	- 2	92	93	3	1/2	Wings, wires and struts		Cleveland, Dec. 4, 1931
St. and A.-St.	920	1,140	- 1	- 3	98	100	1	1/4	Wings, wires and struts		Cleveland, Dec. 10, 1931
	5,060	5,120	-13	-13	94	94	1	—			
A.-St. and snow	4,000	4,820	- 7	- 9	90	80	3 1/2	1/4	Wings, wires and struts		Cleveland, Jan. 21, 1932
A.-St. rain and sleet	4,080	4,410	- 4	- 6	90	88	6 1/2	1/4	Wings, wires and struts		Cleveland, Nov. 14, 1931
A.-St. rain and sleet	3,430	4,800	- 2	-11	94	91	—	*	Leading edges, struts and all rigging	*Iced so heavily had difficulty climbing, white beads of ice	Dallas, Dec. 8, 1931
A.-St. and snow	2,680	3,390	- 6	-10	80	93	3	1/4	Wings, wires and struts		Cleveland, Feb. 21, 1932
A.-St.	2,670	3,350	- 2	- 5	94	92	14	5/8	Wings, wires and struts	Ice uneven on wires and struts, caused excessive vibration	Cleveland, Mar. 2, 1932
St.	880	1,100	- 9	-13	90	95	4	1/4	Wings, wires and struts		Cleveland, Mar. 6, 1932
St.	810	1,500	-14	-19	100	98	5	3/8	Wings, wires and struts	White frosty	Cleveland, Mar. 10, 1932
St.	540	680	-10	-13	98	98	2	1/4	Wings, wires and struts		Cleveland, Mar. 11, 1932
St.-Cu.	1,200	1,430	- 4	- 6	95	95	2 1/2	1/4	Wings, wires and struts		Cleveland, Mar. 19, 1932
St.	430	1,540	- 3	-10	90	93	5	1/2	Wings, wires and struts		Cleveland, Mar. 22, 1932
St.-Cu.	1,180	1,580	- 7	- 8	94	95	4	1/2	Wings, wires and struts		Cleveland, Mar. 31, 1932
A.-St. and snow	2,480	2,650	+ 1	0	98	98	3	1/4	Wings, wires and struts		Cleveland, Jan. 2?, 1932
St.-Cu.	580	1,180	- 4	- 6	97	100	2 1/2	1/2	Wings, wires and struts		Cleveland, Apr. 3, 1932
St. and snow	700	1,430	- 4	-10	90	95	5	1/2	Wings, wires and struts		Cleveland, Apr. 13, 1932
St. and snow	930	2,300	- 6	-15	98	90	8	1/4	Wings, wires and struts	Rough	Cleveland, Apr. 12, 1932
A.-St. and rain	2,670	4,950	- 3	-14	95	88	—	*	Icicles formed straight back from trailing edge of wings	*About one dozen icicles, yellowish rime	Cleveland, Apr. 30, 1932
A.-Cu.	4 200	4,450	-11	-13	70	90	6	1/4	Wings, wires and struts		Cleveland, Apr. 24, 1932
St.-Cu.	850	1,430	- 2	- 4	94	95	5	3/8	Wings, wires and struts		Cleveland, Apr. 28, 1932
A.-Cu.	2,330	2,530	- 2	- 3	93	93					

Meters x 3.28083 = feet

TABLE I. (Cont) FLIGHT OBSERVATIONS MADE DURING THE FORMATION OF ICE ON THE AIRPLANE, CLASSIFIED ACCORDING TO THE TYPE AND THICKNESS OF FORMATION

Cloud or other conditions in which ice formed	Elevation above ground where ice began to form	Elevation above ground where ice ceased to form	Temperature where ice began to form	Temperature where ice ceased to form	Relative humidity where ice began to form	Relative humidity where ice ceased to form	Time interval in which ice formed	Thickness of coating	Parts of airplane where ice formed	Remarks	Place and date of observation
	Meters	Meters	°C	°C	Per-cent	Per-cent	min.	in.	R I M E, L E S S T H A N 1/4 I N C H		
A.-Cu.	3,610	3,870	- 3	- 4	95	85	1	1/8	Wires	Frosty, white	Cleveland, June 8, 1932
A.-St.	4,420	4,570	-12	-14	78	82	10	1/16	Leading edges	Whitish	Chicago, May 9, 1932
St.-Cu.	2,370	2,750	- 2	- 5	94	88	3	1/16	Leading edges	Whitish and smooth	Chicago, May 10, 1932
St.	480	750	- 3	- 4	90	92	1	1/8	Wings, wires and struts		Cleveland, Jan. 4, 1932
St.	430	940	- 1	- 3	94	95	3	Trace	Windshield		Omaha, Dec. 24, 1931
St.	680	2,150	- 9	- 6	95	97	7	Small amount	Leading edges	Light snow at ground but none noted by pilot in clouds	Omaha, Feb. 14, 1932
St.	900	1,150	- 9	-10	92	98	2	1/8	Wings, wires and struts		Cleveland, Feb. 5, 1932
St.	810	980	0	- 1	95	97	1	1/16	Leading edges		Chicago, Feb. 2, 1932
A.-Cu.	5,010	5,150	-18	-20	88	89	15	Very thin	Wings and struts	Neither airplane or instrument showed any vibration	Dallas, Jan. 18, 1932
St.-Cu. and snow	800	990	-10	-12	84	85	4	Thin	Struts	Formed immediately upon entering clouds and melted immediately upon leaving clouds	Chicago, Nov. 25, 1931
St. and rain	4,040	4,300	- 2	- 3	94	94	4	1/16	Leading edges wings and struts	Ice disappeared on descent at 3,600 meters above ground	Chicago, Oct. 13, 1931
St. and rain	980	1,550	+ 1	- 4	94	95	5	1/8	Wires and struts		Cleveland, Oct. 30, 1931
A.-Cu.	3,330	3,610	-18	-20	100	100	7	Thin	Leading edges exposed parts	Smooth, not noticed until after landing	Omaha, Mar. 5, 1932
St.-Cu.	940	1,230	- 6	- 8	84	88	1 1/2	1/8	Wings, wires and struts	Frosty, white	Cleveland, Mar. 1, 1932
A.-St.	3,480	3,980	-13	-17	95	97	9	1/8	Wings, wires and struts		Cleveland, Mar. 16, 1932
St.-Cu.	1,250	1,600	- 9	-12	93	93	3	Small amount	Wires		Cleveland, Mar. 24, 1932
St.	400	680	- 1	- 2	95	96	2	1/8	Wings, wires and struts		Cleveland, Mar. 29, 1932
St.-Cu.	1,740	4,750	- 2	-19	95	100	39	Thin	Leading edges exposed parts	Not noticed during flight, seen after landing	Omaha, Jan. 14, 1932
A.-Cu.	4,080	4,140	-30	-31	68	70	6	1/8	Leading edges and under side of wings		Chicago, Mar. 15, 1932
A.-St.	3,400	4,170	- 4	- 9	93	100	7	1/8	Leading edges and wings		Chicago, Apr. 6, 1932
A.-Cu.	2,400	2,780	-14	-17	89	90	4	1/8	Leading edges and landing gear, cowling and aerometeorograph		Chicago, Mar. 28, 1932
St. and rain	1,100	1,550	+ 1	- 1	99	100	3	1/8	Wings, wires and struts	Rough	Cleveland, Apr. 11, 1932
A.-Cu.	4,350	5,430	-11	-18	70	83	15	Small amount	Wires	Frosty	Omaha, Apr. 26, 1932
A.-Cu.	5,130	5,380	- 7	- 9	62	70	5	1/8	Wires	White, frosty	Cleveland, Oct. 23, 1931
St.-Cu.	830	1,040	+ 1	- 3	90	91	2	3/16	Struts, wires and leading edges, wings		Cleveland, Oct. 17, 1931
St.-Cu.	960	1,290	- 9	-10	90	94	1 1/2	3/16	Wings, wires, struts		Cleveland, Jan. 10, 1932
St.-Cu.	2,390	2,850	- 7	- 8	90	90	2 1/2	1/8	Wings, wires, struts		Cleveland, Jan. 2, 1932
St.-Cu.	390	670	- 7	- 9	92	95	3	1/8	Brace wires only		Chicago, Jan. 8, 1932
St.-Cu.	480	810	- 6	- 8	82	85	3	1/8	Brace wires only		Chicago, Jan. 29, 1932
St.-Cu.	650	1,020	- 7	- 8	90	96	1 1/2	1/8	Wings, wires and struts	Frosty white	Cleveland, Dec. 25, 1931
St.-Cu.	780	980	- 8	-10	90	95	4	1/8	Wings, wires and struts		Cleveland, Feb. 4, 1932
St.-Cu.	1,280	1,300	- 5	- 5	95	95	1/3	1/8	Wires	Frosty white	Cleveland, Feb. 29, 1932
St.-Cu.	410	470	- 5	- 6	95	96	1	Thin	Brace wires only	Flaky	Chicago, Jan. 3, 1932
St.-Cu.	540	650	- 9	-11	81	86	2	Small amount	Leading edges		Chicago, Jan. 24, 1932
St.-Cu.	1,250	1,530	- 4	- 7	88	94	4	1/16	Leading edges, struts and wires		Chicago, Nov. 8, 1931
St.-Cu.	720	1,070	- 2	- 5	84	89	1	Light	Leading edges and wings		Chicago, Dec. 26, 1931
St.-Cu.	530	910	- 5	- 7	88	94	3	1/16	Leading edges		Chicago, Feb. 3, 1932
St.-Cu.	640	930	- 3	- 6	84	93	1	Thin	Leading edges		Chicago, Feb. 24, 1932
A.-St, Sleet and snow	2,600	4,150	- 5	-15	92	87	—	1/8	Wings and struts		Cleveland, Apr. 10, 1932
A.-Cu.	4,860	5,010	- 6	- 9	85	85	3	1/16	Leading edges struts and wings		Chicago, Oct. 8, 1931
A.-Cu.	4,110	4,190	- 4	- 4	96	98	5	1/8	Leading edges struts and wings		Chicago, Oct. 23, 1931
A.-Cu.	3,550	3,810	-11	-15	100	100	7	Thin	Wires, wings and leading edges, struts	Ice disappeared on descent at 1,500 meters above ground	Dallas, Feb. 24, 1932
A.-Cu.	4,840	4,900	-18	-20	85	86	5	1/8	Wings, wires and struts		Cleveland, Feb. 26, 1932
A.-St.	2,580	2,990	-15	-18	72	74	4	Thin	Leading edges		Chicago, Feb. 1, 1932
A.-St.	4,350	4,490	-19	-21	90	90	3	1/16	Wires	Ground lights visible through clouds	Cleveland, Feb. 27, 1932
A.-St.	1,940	2,140	-10	-12	90	96	2	Small amount	Wires and struts		Cleveland, Feb. 15, 1932
A.-St.	4,480	4,910	-13	-17	84	88	7	1/8	Leading edges	Soft, made airplane hard to handle	Omaha, Dec. 8, 1931
A.-Cu.	3,640	3,780	- 4	- 8	97	94	2	1/16	Wires		Cleveland, May, 7, 1932
St.-Cu.	4,850	5,050	-11	-15	63	73	2	Small amount	Leading edges		Omaha, May 26, 1932
A.-St.	3,490	4,440	0	- 8	88	95	11	1/32	Struts, wires and leading edges, wings	Rough	Omaha, May 24, 1932
St.-Cu.	3,770	4,680	- 9	-14	72	40	12	1/8	Leading edges struts and wires		Chicago, Apr. 21, 1932
St.-Cu. and rain	2,180	2,860	- 1	- 2	100	99	1	1/8	Wires and struts		Cleveland, May 11, 1932

Meters x 3.28083 = feet

TABLE I. (Cont) FLIGHT OBSERVATIONS MADE DURING THE FORMATION OF ICE ON THE AIRPLANE, CLASSIFIED ACCORDING TO THE TYPE AND THICKNESS OF FORMATION

Cloud or other conditions in which ice formed	Elevation above ground where ice began to form	Elevation above ground where ice ceased to form	Temperature where ice began to form	Temperature where ice ceased to form	Relative humidity where ice began to form	Relative humidity where ice ceased to form	Time interval in which ice formed	Thickness of coating	Parts of airplane where ice formed	Remarks	Place and date of observation
	Meters	Meters	°C	°C	Per-cent	Per-cent	min.	in.	CLEAR ICE, THICKNESS UNKNOWN		
Mist and A.-Cu.	1,900	3,500	- 1	-10	70	90	12	?	Leading edges and aerometeorograph	Small globules of clear ice	Omaha, Feb. 23, 1932
A.-St.	2,350	2,760	0	- 2	91	89	2	?	All over airplane	Clear drops, much moisture on airplane before ice formed	Chicago, Dec. 30, 1931
Rain and St.-Cu.	800	1,060	0	- 2	88	90	5	?	Wires and metal parts, not on wings	Smooth	Omaha, Oct. 29, 1931
St.-Cu.	350	730	- 2	- 4	84	86	3	?	Leading edges	Rough	Chicago, Jan. 15, 1932
Rain (Below A.-St.)	4,220	5,000	- 3	- 7	95	83	20	?	Wires and leading edges, wings and struts	About the size of raindrops	Dallas, Jan. 18, 1932
									RIME, THICKNESS UNKNOWN		
St.-Cu. rain and sleet	5,150	3,950	0	- 5	100	60	6	?	Leading edges wings, struts and wires	Like small raindrops, white	Dallas, Feb. 15, 1932
St.-Cu. and rain	3,810	4,440	- 3	- 7	100	97	13	?	Wings, struts, rigging and aerometeorograph	White beads	Dallas, Feb. 16, 1932
St.-Cu. and sleet	2,400	2,900	0	- 3	100	98	5	?	Leading edges, struts and wings	Like frozen raindrops, white	Dallas, Feb. 22, 1932
St.-Cu. rain and sleet	3,590	4,810	- 1	- 8	99	94	25	?	Struts, wires and trailing edge of wings	Whitish, about size of raindrops, flattened into flakes	Dallas, Jan. 22, 1932
A.-St.	4,030	4,330	- 9	-12	85	93	8	?	Struts and bottom of wings	Smooth	Chicago, Dec. 31, 1931
A.-St. rain and sleet	3,120	4,640	- 2	-12	82	93	24	?	Leading edges wings, struts and rigging wires	Smooth	Dallas, Dec. 1, 1931
									RIME, AND CLEAR ICE IN SAME OBSERVATION		
A.-Cu.	4,400	4,700	- 3	- 5	62	85	5 1/2	1/4	Wings, wires and struts	Inner coat frosty, outer coat clear	Cleveland Oct. 24, 1931
St.-Cu.	630	1,160	- 6	-10	62	93	8	—	Leading edges	Smooth, clear and solid, except rough whitish strip center of forward edge of wing, adhering very tightly to airplane, thickest at exact center of and leading edge and diminishing within several inches of leading edge	Chicago, Dec. 6, 1931
St.-Cu.	1,820	2,600	- 7	-12	84	93	4 1/2	1/2	Wings, wires and struts	Semiclear ice and semifrosty	Cleveland, Nov. 2, 1931
St.-Cu. snow and sleet	3,280	4,540	- 1	- 9	98	98	20	Heavy	Leading edges, struts, wings and wires	Snow froze first as whitish ice, then sleet froze, forming outer coat of clear ice	Dallas, Mar. 30, 1932

Meters x 3.2808 = feet

(Conclusion of Table I)

TABLE II.

Type	Thickness	No. of cases	Average temperature at which formation occurred	Average temperature interval in which formation occurred	Average relative humidity at which formation occurred	Average relative humidity interval in which formation occurred. (+ indicates higher humidity at end of formation than at beginning; vice versa.)	Average time during which formation occurred	Average height above ground where formation occurred	Average thickness of stratum in which formation occurred
			°C	°C	Percent	Percent	min.	meters	meters
Clear ice	1/4 in. or more	19	-5.8	3.5	92	+ 2	7.5	2,476	576
Clear ice	Less than 1/4 in.	19	-5.9	2.4	90	+ 3	3.7	1,943	499
Clear ice	Unknown	5	-3.1	3.8	86	+ 2	8.4	2,272	696
Clear ice	All	43	-5.5	3.1	90	+ 2	6.3	2,245	562
Rime	1/4 in. or more	50	-6.3	3.3	92	+ 3	6.6	2,151	522
Rime	Less than 1/4 in.	52	-8.6	2.7	89	+ 2	4.8	2,482	395
Rime	Unknown	6	-5.2	5.3	93	- 2	13.7	3,764	828
Rime	All	108	-7.3	3.1	91	+ 2	6.1	2,399	479
Clear ice and rime during same observation	All	4	-6.6	4.8	87	+10	9.5	2,891	718

TABLE III.

Types	Thickness	Number of cases at Chicago	Cleveland	Dallas	Omaha
Clear ice	1/4 in or more	10	6	0	3
Clear ice	Less than 1/4 in.	3	2	1	11
Clear ice	Unknown	2	0	1	2
Clear ice	All	15	8	2	16
Rime	1/4 in. or more	4	38	4	1
Rime	Less than 1/4 in.	20	22	2	8
Rime	Unknown	1	0	5	0
Rime	All	25	60	11	9
Clear ice and rime during same observation	All	1	2	1	0

TABLE IV.

	Average temperature during the ice formations as obtained from data in Table I for		Average temperature for Nov. 1931 to April, 1932, incl., for the heights		Average amount of low clouds. 8:00 a.m. E.S.T. for Nov., 1931 to April, 1932, incl. (Scale 0-10)	Average amount of intermediate clouds. 8:00 a.m., E.S.T., for Nov. 1931 to April, 1932, incl. (Scale 0-10)
	Clear ice	Rime	2,245 meters*	2,399 meters**		
Chicago	-4.8	-8.1	-2.6	-3.3	4.3	1.2
Cleveland	-2.8	-6.8	-2.8	-3.4	5.0	2.0
Dallas	-3.0	-7.1	6.5	4.9	4.4	0.6
Omaha	-7.4	-9.5	-0.5	-1.2	4.8	0.8

* Average height above ground at which clear ice formed.
** Average height above ground at which rime formed. (See Table II.)

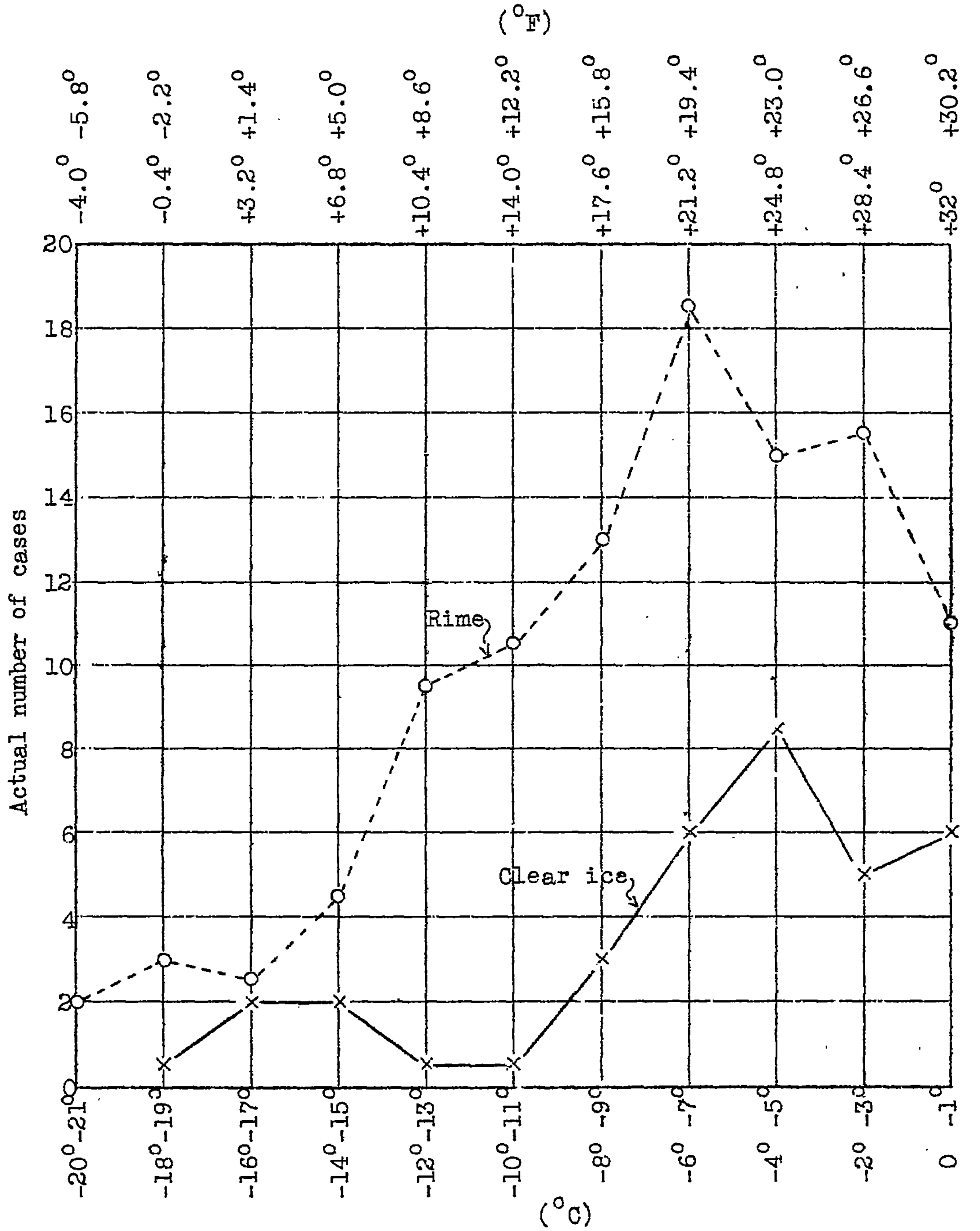

Fig.1 Actual number of cases when clear ice and rime formed at various temperatures, the latter representing the mean of the temperature range through which each formation occurred.

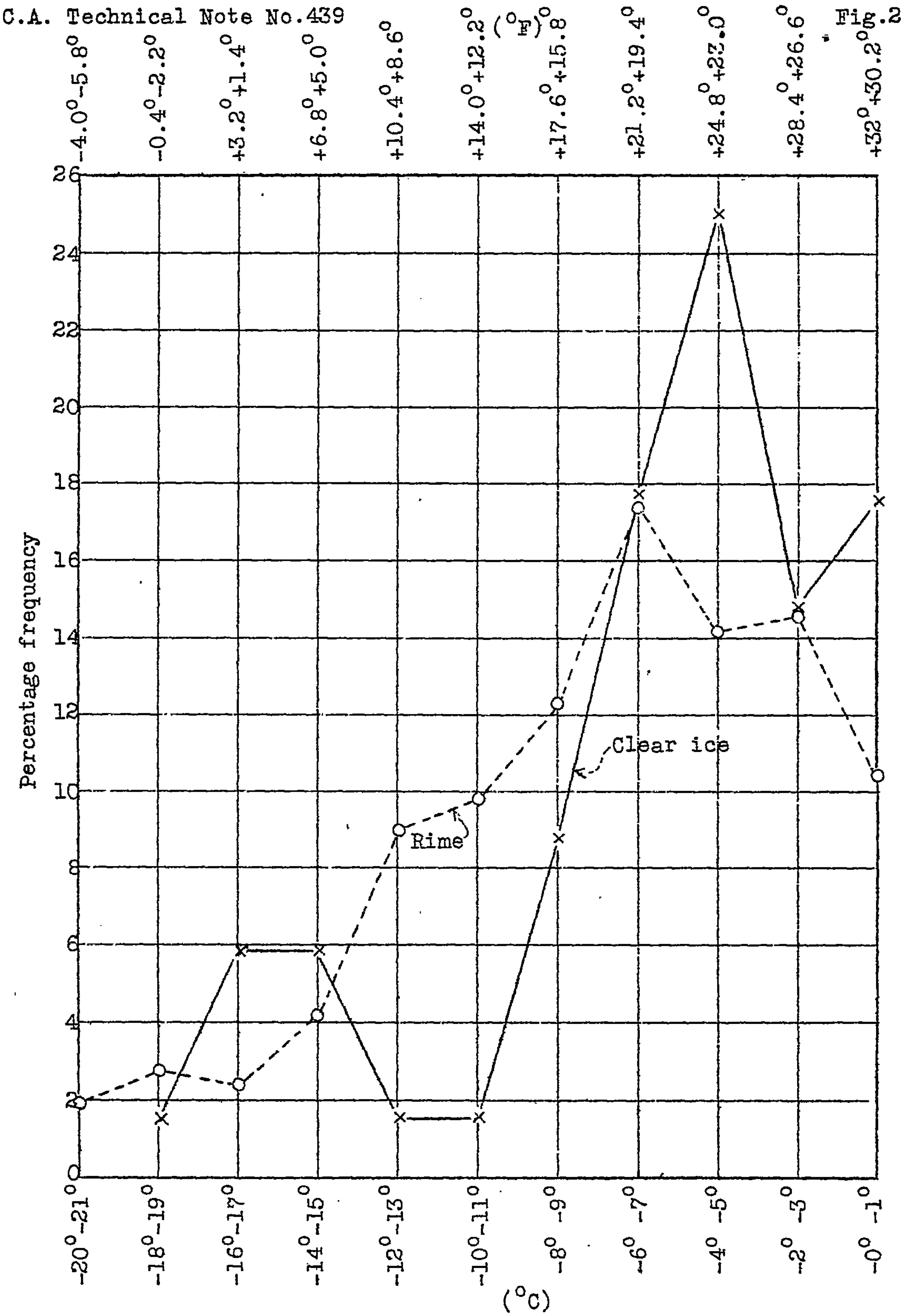

Fig.2 Percentage frequencies of clear ice and rime formations at various temperatures, the latter representing the mean of the temperature range through which each formation occurred

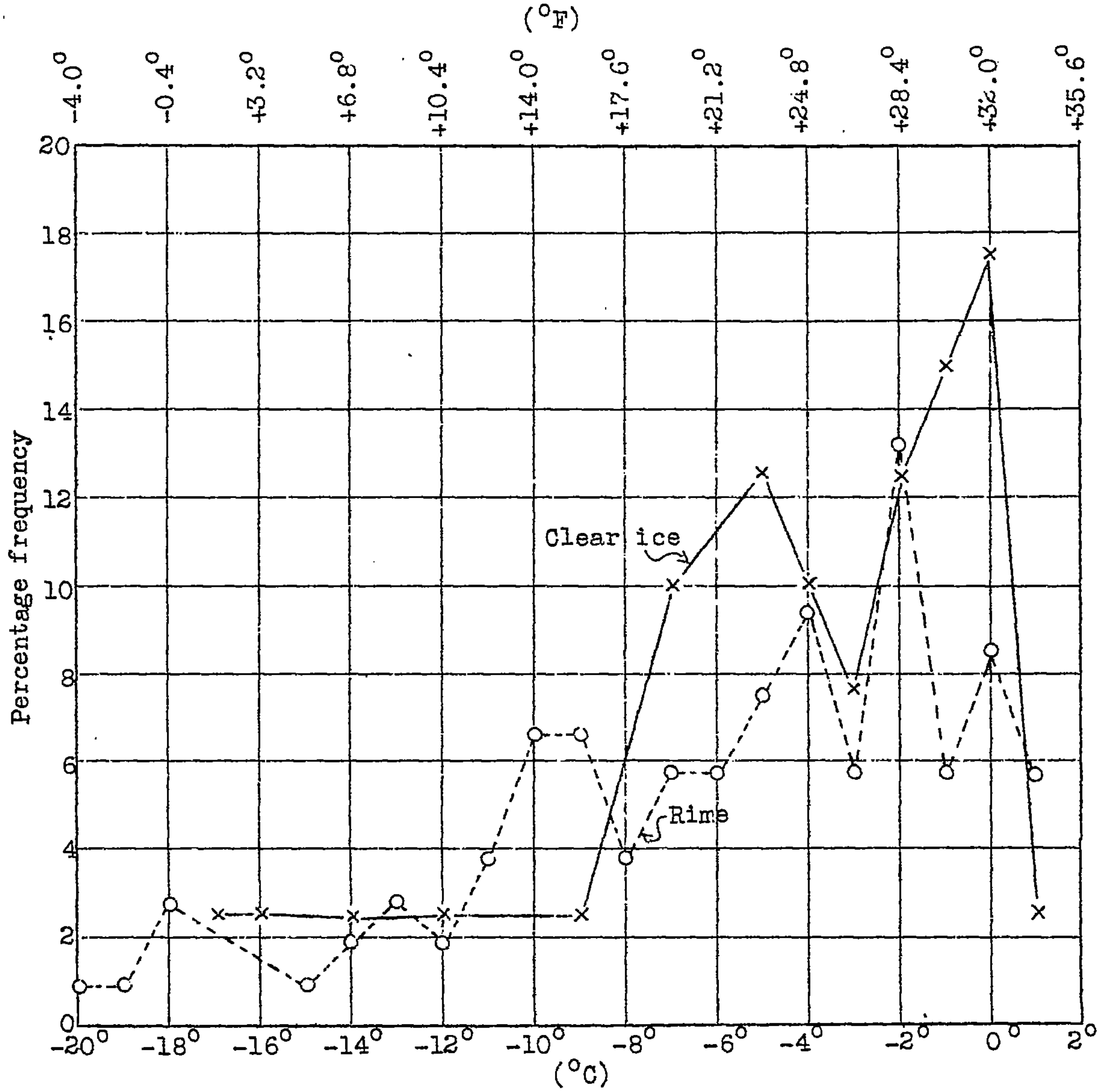

Fig.3 Percentage frequencies of clear ice and rime formation at the temperatures at which the ice began to form.

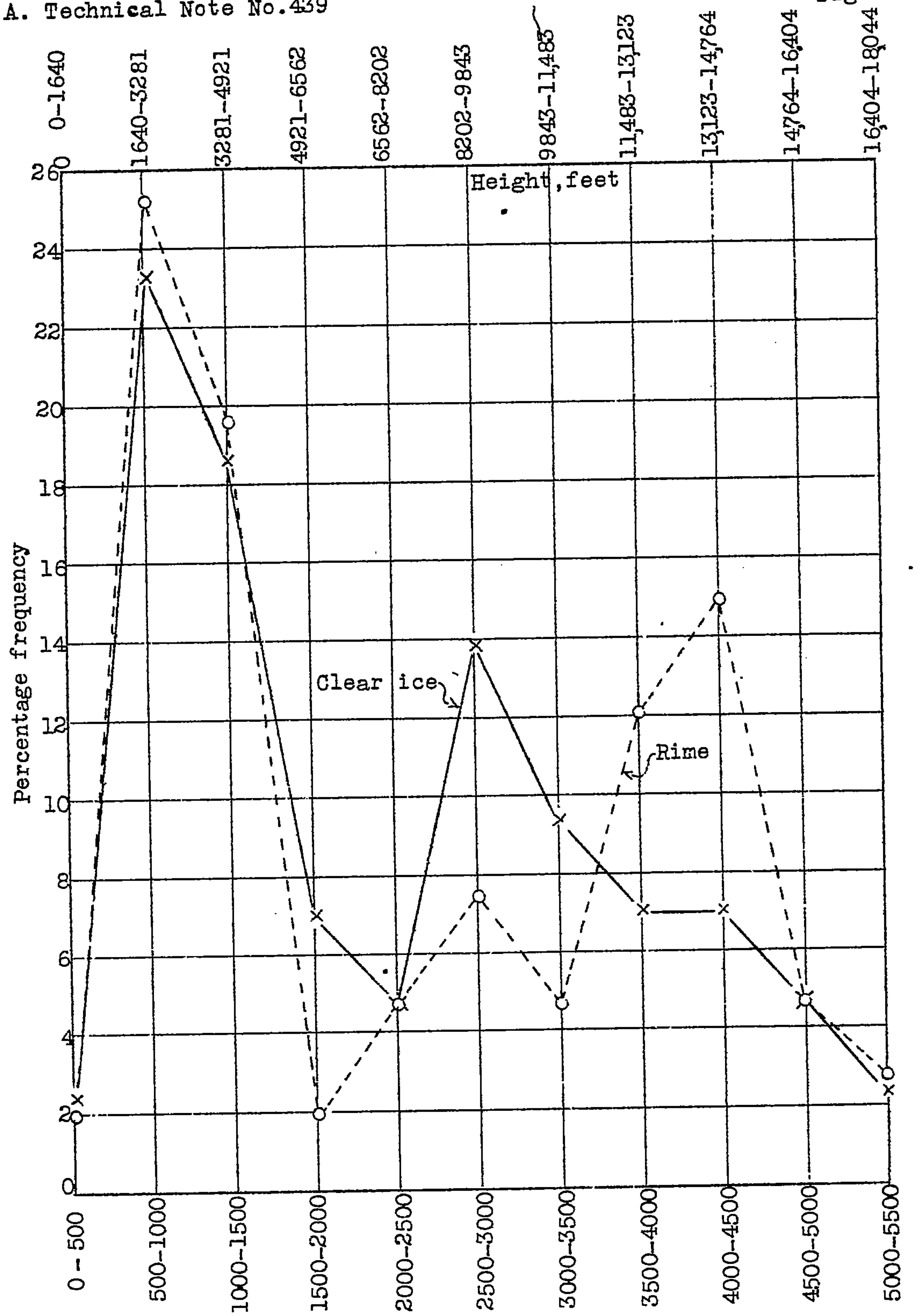

Fig.4 Percentage frequencies of clear ice and rime formations at various heights above the ground, the latter representing the mean of the height interval in which the formations occurred.

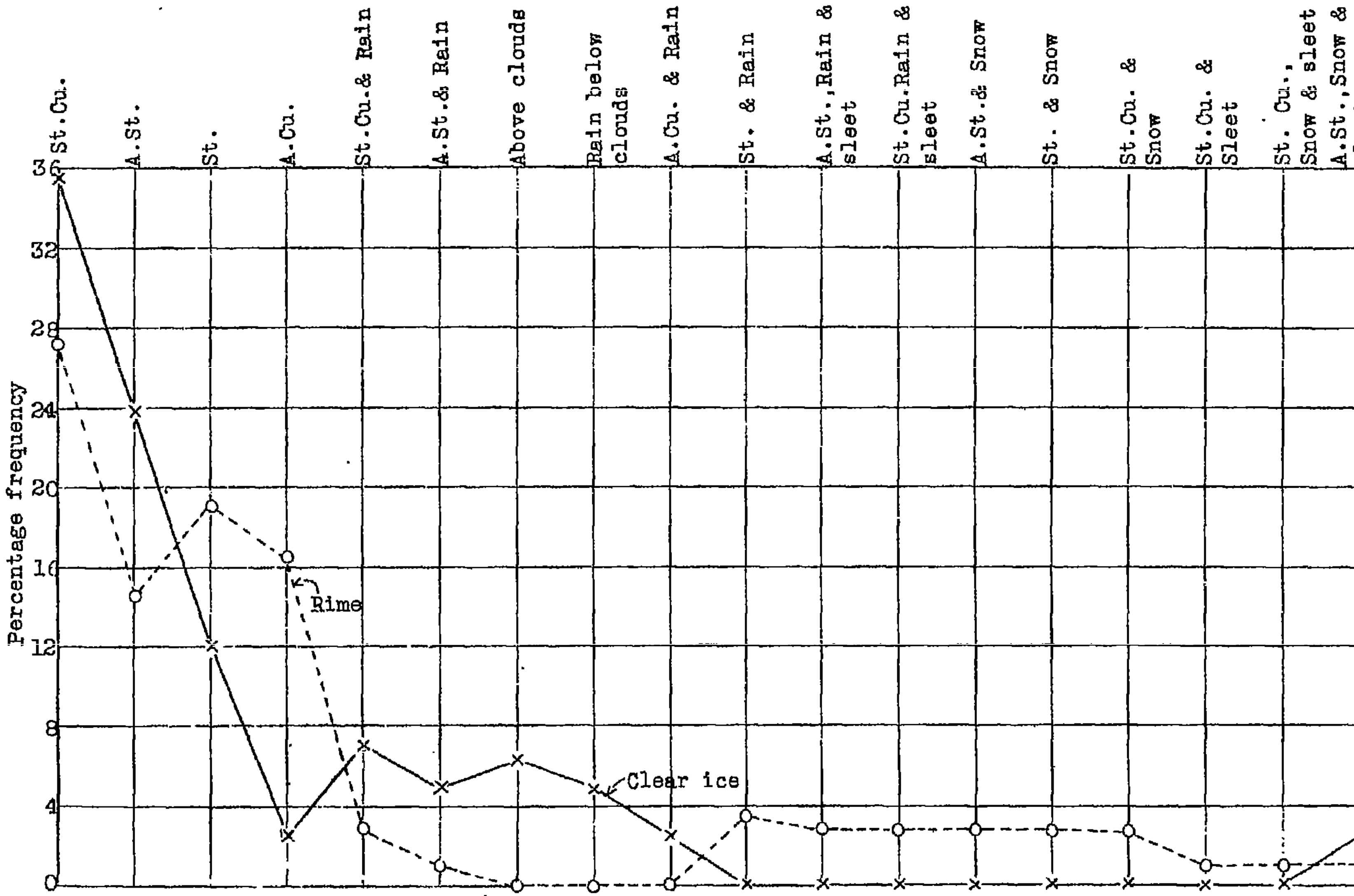

Fig.5 Percentage frequencies of clear ice and rime formations for various cloud and weather conditions.